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Infrared Imaging of Faculae at the Deepest Photospheric Layers

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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We have used the NOAO 58 x 62 InSb array and the National Solar Observatory McMath telescope to image the deepest photospheric layers of three active regions at the 1.63 μm opacity minimum. At 1.63 μm, faculae are darker than the photosphere, with a measured contrast of at least 2% at positions on the disk between approx. $0.75 < \mu < 1.0$. Near the limb, at $\mu < 0.5$, they are brighter than the photosphere, as in the visible. At intermediate $0.5 \leq \mu \leq 0.75$, they are difficult to detect at 1.63 μm. The observation that faculae and their immediate surroundings exhibit a clear deficit of brightness temperature near disk center at 1.63 μm seems to rule out the "hillock" model put forward to explain their center-to-limb contrast variation. The transition from bright faculae at $\mu = 1$ in visible continuum, to dark faculae at 1.63 μm seems to be explained by existing "hot wall" models of these structures. We also discuss the imperfect spatial correspondence found between dark faculae and bright Ca K plage in terms of possible differences in size between photospheric flux tubes that give rise to Ca K plages. Hydrogen opacity; Infrared detectors; mu = approx.

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Preface

We are grateful to L. Gilliam at NSO Sac Peak for the corollary Ca K and red continuum data, and to R. Probst of NOAO for the initial setup of the infrared array. This work was carried out at CRI, Inc., under NSF grant ATM 8619733. D. Lynch was supported at The Aerospace Corporation under contract number F04701-85-C-0086-P00019.

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I. Introduction

The reason for the excess brightness of small-diameter magnetic flux tubes (faculae) in the visible continuum and lines is currently the subject of considerable interest. For one, recent evidence indicates that changes in the area, intensity, and distribution of faculae probably provide the main contribution to changes in total solar irradiance over the 11 year activity cycle (Foukal and Lean, 1988; Livingston, Wallace, and White, 1988; Schatten, 1988; Kuhn, Libbrecht, and Dicke, 1988). Information on their internal structure also provides insight into the dynamics of the intensification and evolution of photospheric magnetic fields (Spruit, 1976; Wilson, 1981; Chapman, 1984; Chapman and Gingell, 1984; Deinzer *et al.*, 1984; Ferrari *et al.*, 1985; Knölker and Schüssler, 1988; Steiner and Pizzo, 1989).

In paper I (Foukal, Little, and Mooney, 1989), we showed that faculae in active regions tend to be dark, rather than bright, when imaged at the minimum of photospheric opacity, around 1.63 μm. Earlier observations by Worden (1975) had suggested the presence of dark 1.63 μm structures in the network. However, the relatively poor spatial resolution achievable in the IR with the small coelostat used for the observations reported in Paper I, together with flat fielding difficulties caused by cirrus clouds, made it difficult to draw conclusions about the spatial correspondence between infrared faculae and Ca K plages, and their behavior in the IR as a function of position on the disk.

In a recent paper by T. Ayres (Solar Phys., **124**, 15 [1989]), it is argued that the violet continuum near 0.4 μm might be more suitable than the 1.63 μm region, for studying the deep photosphere. This might be true if the continua were equally accessible at the two wavelengths. In practice, solar line opacity in the 40 Å IR window we used here is negligible, whereas it is questionable whether true continuum can be found anywhere around 0.4 μm, even using the subangstrom spectral purity of a spectroheliograph.

In this report, we present better 1.63 μm images of several active regions obtained at the McMath telescope under good conditions. We also compare our results with some theoretical models of facular structure.

II. Observations and Reduction

Our observations were carried out on 1988 June 10–12, using the main heliostat of the National Solar Observatory McMath telescope at Kitt Peak. In place of the usual image-forming mirror, a 20 cm objective lens of 9 m focal length was used to produce an image scale of 35 arcsec mm^{-1}. The IR beam was attenuated by a factor of $\sim 10^5$ using neutral density filters before being transmitted to the IR array. An interference filter described in Paper I was used to define a 40 Å infrared passband centered at 1.627 4 μm.

The infrared detector was a 58 x 62 InSb array (Fowler *et al.*, 1987) with a focal plane dimension of 4.4 x 4.7 mm. Frequent flat-fielding of the array was carried out to remove array defects, gain variations, and low-level interference fringes. Tests indicate a pixel-to-pixel photometric noise level of $\sim$ 0.15% rms, over 8 x 8 pixel areas of the array.

Simultaneous images were obtained with a visible light CCD viewing the same scene as the IR array through a beam splitter. An interference filter centered $\sim$ 3860 Å was chosen to show both sunspots and faculae as the IR observations were made.

In addition to the above observations obtained at Kitt Peak, we have made use in this study of daily full disk spectroheliograms in Ca K + 0.38 Å and Hα 4.3 Å (continuum) daily images obtained at Sacramento Peak. These corollary data have been used in the analysis to define the locations of plages and sunspots, respectively. The four active regions observed are identified in Table 1, along with their disk positions and dates of observation.

Table 1. Visibility of Faculae at 1.63 μm

Active Region	Date	μ-value	Facular Appearance
SPO 7657............	1989 Jun 10	0.98–0.87	Dark
SPO 7658	1989 Jun 10	0.75–0.55	Not detected
SPO 7652	1989 Jun 11	0.40–0.00	Bright
SPO 7657	1989 Jun 11	0.98–0.92	Dark
SPO 7658	1989 Jun 11	0.88–0.75	Dark (faint)
SPO 7652	1989 Jun 12	0.33–0.00	Bright
SPO 7653	1989 Jun 12	0.51–0.00	Bright
SPO 7657	1989 Jun 12	0.97–0.87	Dark
SPO 7658	1989 Jun 12	0.95–0.83	Dark

III. Results

A. APPEARANCE OF FACULAE AT 1.63 μm AND AT Ca K ON THE DISK AND NEAR THE LIMB

Figure 1 shows the appearance (with similar orientation and scale) of active region SPO 7658 at a heliocentric position of $\mu = \cos\theta - 0.89$ on the disk, observed in red continuum (Hα 4.3 Å), at Ca K, and in the infrared continuum at 1.63 μm. The infrared image, (*c*), shows dark structures coinciding with the positions of all the spots seen in the red continuum, (*a*). But in addition, it shows an extended and obvious dark structure (*indicated by the arrow*) at a location where no spot is seen in the red.

The Ca K picture, (*b*), shows that this dark IR structure coincides with some of the brightest and most extended plage in this active region. We see further that the leftward extension of this plage in panel (*b*) corresponds in panel (*c*) to more dark structures in the IR, again located where no spots are seen in panel (*a*).

These examples in Figure 1 show particularly clearly that in 1.63 μm images, faculae appear darker than the photosphere rather than brighter as they do throughout the visible. Additional examples of this 1.63 μm darkness of faculae can be seen in Figure 1. For instance, just above the lowermost sunspot, two small dark structures are seen at 1.63 μm that again show no corresponding spots in panel (*a*), but coincide with plage in panel (*b*). Yet another case is seen to the immediate right of the largest spot; several dark 1.63 μm structures are evident at a location where again no spots are visible in panel (*a*). These findings for the active regions observed here agree with our previous results (Paper I) for three other active regions observed in that study. Thus we infer that the tendency to darkness of faculae at 1.63 μm is general.

Further insight into the behavior of faculae on the disk at 1.63 μm can be gained from examination of Figure 2, which shows the active region SPO 7657, located at $\mu = 0.92$. As in Figure 1, all the spots seen in red continuum are seen as dark structures at 1.63 μm. In addition, the infrared image shows many dark structures that fall within the Ca K plage contours, but do not coincide with any spots visible in red continuum. It is interesting that although the dark 1.63 μm faculae fall within the Ca K plage contours, the correlation between darkness at 1.63 μm and brightness at Ca K is far from perfect.

There appears to be a tendency in Figures 1 and 2 for the brightest plage areas to include the most prominent dark faculae, although their exact coincidence is hard to judge here without precisely coregistered and photometrically calibrated Ca K plage images. Given that the facular magnetic flux tubes observed at 1.63 μm are confined to smaller areas in the deep photosphere than those in the chromosphere observed in Ca K, it is not too surprising to find that the spatial match is less than perfect. The residual gain nonuniformities of the CCD that are evident in

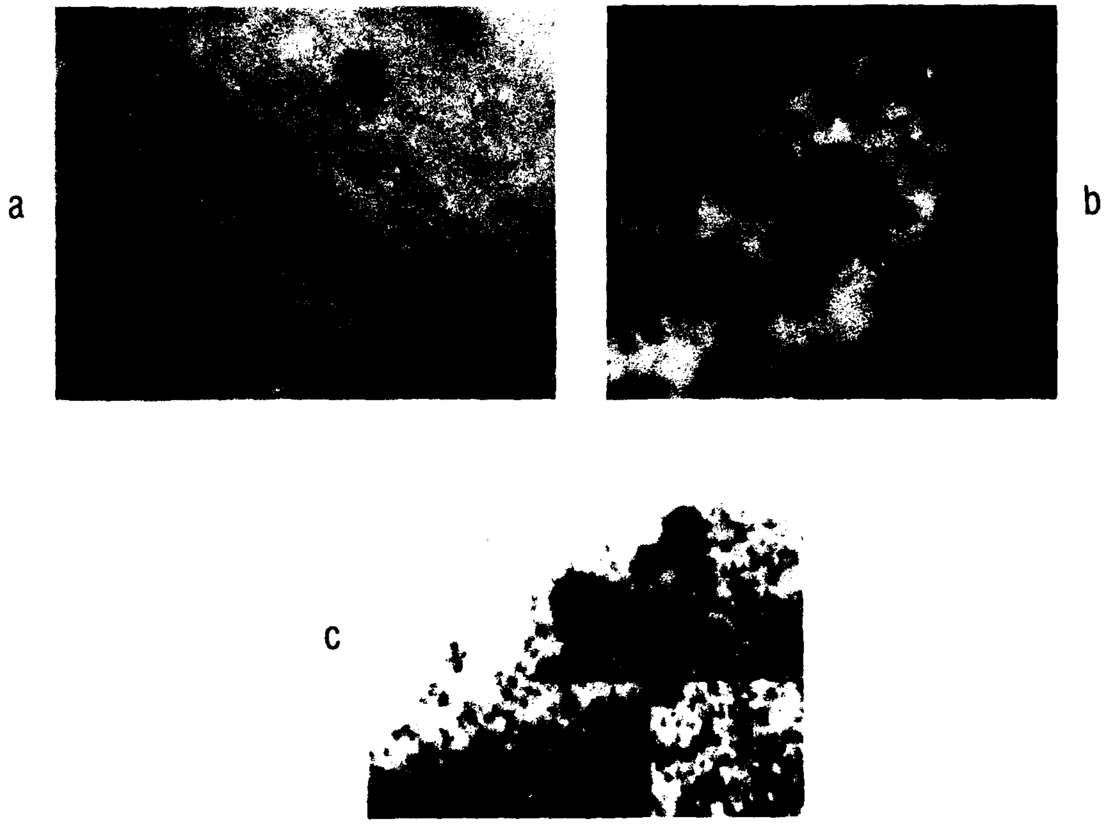
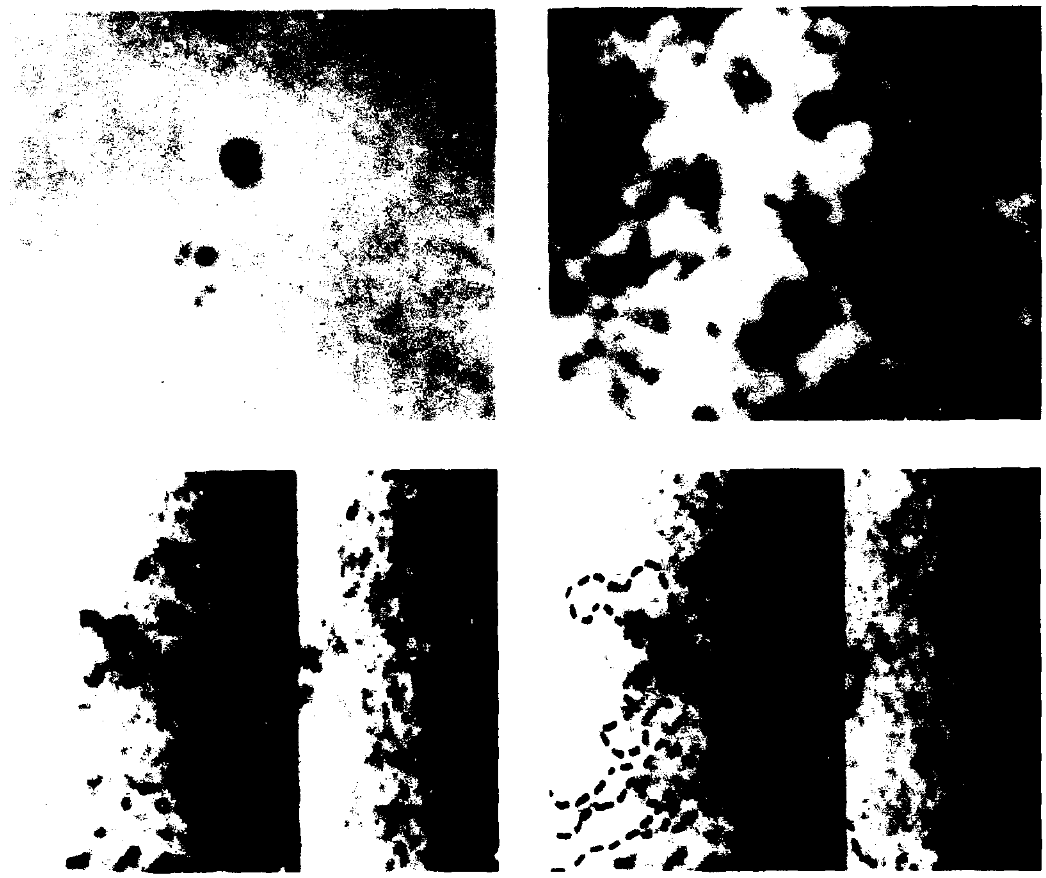


Figure 1. Images of active region SPO 7658 on 1988 June 12 in (a) Hα 4.3 Å at 13:20 UT, (b) Ca K + 0.38 Å at 13:41 UT, and (c) 1.63 μm at 15:35 UT. The field of the 1.63 μm image is ~ 155 x 165 in. The scale and orientation of the three images are similar. The arrow indicates the facular area discussed in the text.



a b c d

Figure 2. Images of active region SPO 7657 on June 12 in (a) Hα 4.3 Å at 13:20 UT, (b) Ca K + 0.38 Å at 13:41, and (c) 1.63 μm at 14:55 UT. Image (d) is the same as (c), but with the contours of the brightest Ca K plage from (b) drawn in. The abrupt change in brightness near the middle of panels (c) and (d) is caused by splicing together of two images whose limb-darkening was imperfectly removed (at below the 1% level).

Figure 2 as brightness gradients across the field of view may also mask some low-level facular signals.

Nevertheless, we note that in certain areas of the Ca K plage contour [as in the upper left in Figure 2 panel (*d*)], a large part of a plage area of apparently uniform brightness is entirely devoid of dark faculae, while next to it, an area of similar size and Ca K brightness is filled with dark faculae. This behavior is difficult to explain as an effect of either filling factor or of detector noise.

The appearance of faculae in the violet and at 1.63 μm near the limb is illustrated in Figure 3. Panel (*a*) shows the high photosphere of the active region imaged at 3860 Å, and a small spot and bright faculae are clearly seen. Panel (*b*) shows that the same faculae are still bright at 1.63 μm, when viewed closer to the limb than $\mu \sim 0.5$, as seen here.

B. FACULAR INTENSITY CONTRAST AT 1.63 μm

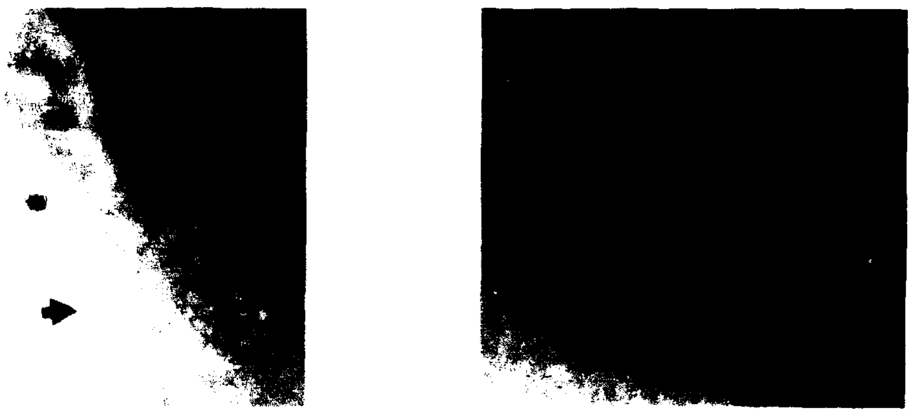
A lower limit to the 1.63 μm contrast of these faculae can be estimated from Figure 4(*a*), which shows intensity scans performed through the structures shown in Figure 1 panel (*c*). The six scans shown are oriented vertically in Figure 1, panel (*c*). They cross the umbra of the largest sunspot [the large dip of ~ 25% contrast to the left in Figure 4(*a*)] and continue to the bottom of Figure 1, panel (*c*). The intensity depression caused by the large dark 1.63 μm structure indicated by the arrow in Figure 1, panel (*c*) is seen to the right in Figure 4(*a*). It can be seen that its 1.63 μm intensity is ~ 2% below that of the photosphere.

Photometry in which precautions have been taken to reduce scattered light indicates an umbral intensity ~ 50% of photospheric intensity at 1.67 μm for large spots (Albregtson and Maltby 1981). This suggests that the scattering and blurring in our observations reduce the contrast of a structure of the size of the largest spot in Figure 2(*a*) by about a factor 2. Since the dark facula indicated by the arrow in Figure 1(*c*) has a comparable scale of ~ 30 in., we expect that its true contrast at 1.63 μm is at least 4%.

Judging from the appearance of this dark facular area in Figure 1(*c*), it consists of a cluster of smaller faculae. In that case, the true contrast of each small element (whose contrast would be reduced proportionately much more than that of the large umbra discussed above) must be considerably larger than even 4%. The main point here is that even the contrast of 2%–4% seen in IR continuum in these dark faculae significantly exceeds the contrast ~ 0.1% measured in the green continuum with comparable spatial resolution in bright faculae at similar heliocentric angle (Foukal and Fowler, 1984).

Figure 4(*b*) shows eight traces of the 1.63 μm intensity plotted horizontally across Figure 2(*c*). As in Figure 4(*a*), the deep (~ 20%) depression is caused by the largest spot. The most prominent dark faculae seen to the left of the largest spot in Figure 2(*c*) and (*d*) produce the ~ 2% intensity depressions near the center of Figure 4(*b*).

a



b

Figure 3. Two simultaneous images of active region SPO 7653 taken at 15:45 UT on 1988 June 12. Image (a) was taken in a passband centered at 3860 Å; image (b) is taken at 1.63 μm. The limb can be seen in the upper right.

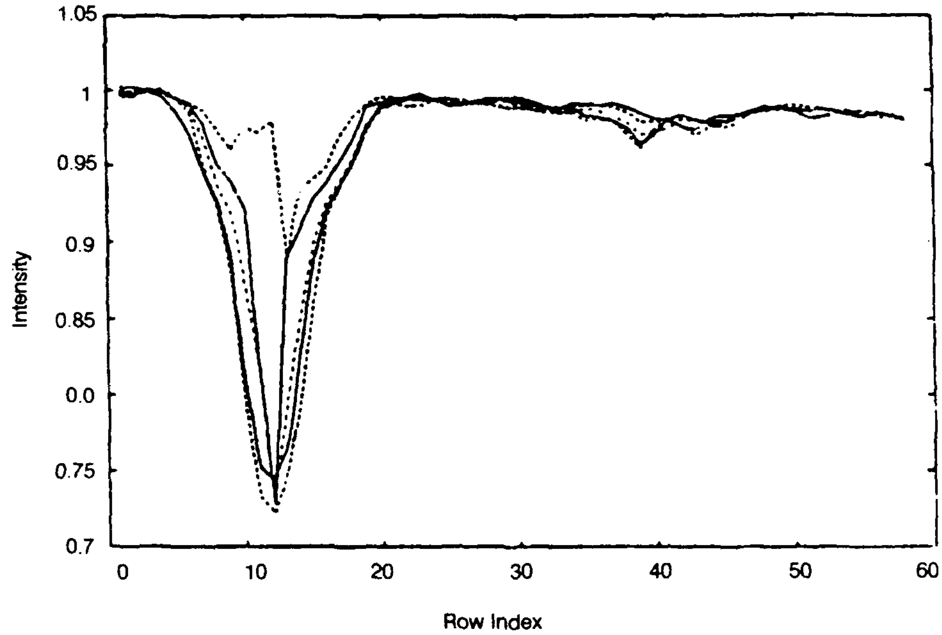


Fig. 4a

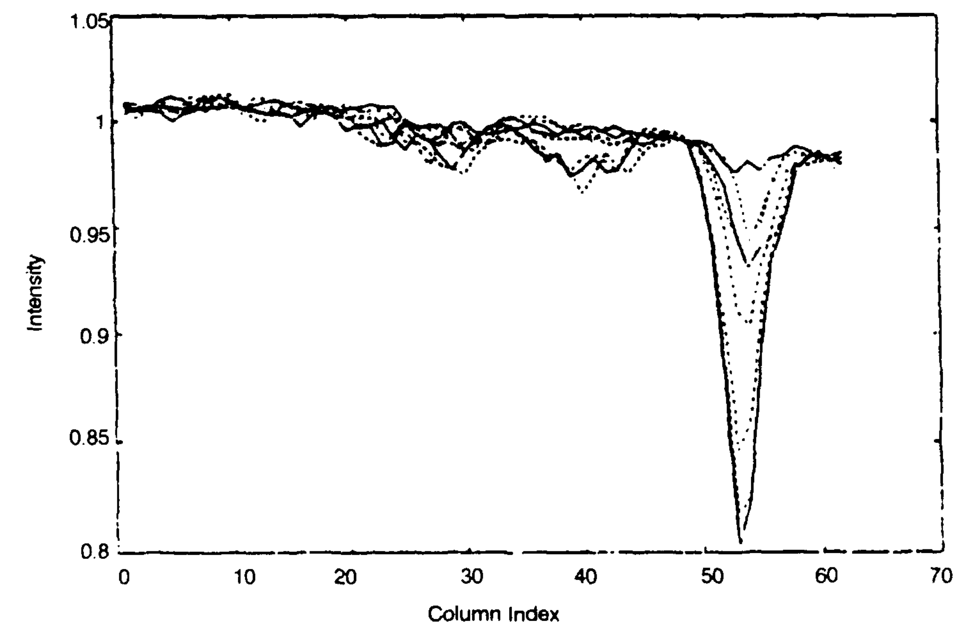


Fig. 4b

Figure 4. Intensity ploted against position (*upper panel*) along six (*horizontal*) raster lines in Fig. 1(c) and (*lower panel*) along eight (*vertical*) raster lines in Fig. 2(c)

The appearance of faculae at 1.63 μm (dark or bright) as a function of disk position in three active regions over three days is summarized in Table 1. Between $\mu = 1.0$ (disk center) and $\mu - 0.75$, the faculae are seen dark. Between $\mu - 0.5$ and the limb, they are bright. In an annular region between $\mu - 0.5$ and $\mu - 0.75$, faculae are below our visibility threshold.

IV. Interpretation and Conclusions

The most important factor to be considered in comparing these observations with theoretical models is our limited spatial resolution relative to the diameter of facular flux tubes inferred from other observations (e.g., Zayer, Solanki, and Stenflo, 1989). For instance, the most complete theoretical model of small-diameter flux tubes (Deinzer *et al.*, 1984; Knölker and Schüssler, 1988) predicts an excess of brightness temperature, T_b, of the small-diameter (~ 0.3 in.) flux tube itself at disk center. This excess T_b persists at 1.63 μm (Knölker, 1989, private communication). However, the radiative leak into the flux tube causes a cooling of its surroundings (Spruit, 1976), so that the total radiative flux integrated over the magnetic tube and its surroundings (out to several arcsec) must closely resemble that of an equal area of undisturbed photosphere.

This flux balance must hold, since in this model, the main effect of the magnetic tube is to laterally redistribute the upward convective and radiative fluxes. When grey radiative transfer in LTE is included in such a model (Grossmann-Doerth *et al.*, 1988), the total intensity of the flux tube and its surroundings near $\mu = 1$ is found to be a few percent lower than the undisturbed photospheric value at 1.63 μm, while at 5000 Å, it is less than a percent greater (Schüssler, 1989, private communication). This brightening at shorter wavelengths is consistent with photometric observations in the green at 5256 Å (Foukal and Fowler, 1984) and in the near-infrared at 8660 Å (Lawrence, Chapman, and Herzog, 1988), both of which show excess facular brightness of between 0.1 and 1% near $\mu = 1$.

On the other hand, our finding that T_b is decreased over areas that include faculae and their immediate surroundings is harder to understand in terms of a "hillock" model of faculae put forward by Schatten *et al.* (1986). In that model, the faculae are interpreted as the sites of increased advection of heat from below by systematic upflows. This increased local heat input is considered to cause heating of the facular subphotospheric layers and to increase their pressure scale height, causing an outward perturbation at the photospheric $\tau = 1$ surface, thus a "hillock."

However, the underlying temperature excess of 4%–10% (Schatten *et al.*, 1986) which is fundamental to the model would produce a very noticeable increase of T_b at $\mu = 1$. Unlike the hot wall model, the hillock model postulates an excess local heat input, so this excess T_b would not be compensated by any cooling of surrounding photosphere. This fact, and also the depth of excess subphotospheric heating below the hillock, taken to extend to several thousand km below $\tau = 1$, makes it difficult to understand how the deficit of T_b at 1.63 μm that we see here could be consistent with this model.

Although the excess T_b expected in the hillock model would be somewhat reduced by the increase of H^- opacity with temperature, an easily observable increase in T_b must still be seen in a structure whose temperature is several percent higher than its surroundings. Based on the above reasoning, we suggest that the hillock model can be ruled out with reasonable certitude as an

explanation of faculae. More generally, our observation seems difficult to explain by any facular heating model that involves a net excess of energy deposition in the facular region and in its immediate surroundings.

Deinzer *et al.* (1984) show the computed center-to-limb contrast behavior in visible continuum of a region containing facular flux tubes. They find that for a theoretical flux tube that corresponds most closely to semiempirical facular models, the structure and surroundings appear dark for $\mu \geq 0.65$, exhibit little contrast between $0.65 \leq \mu \leq 0.35$, and appear bright closer to the limb than $\mu = 0.35$. Our results suggest that the region of low facular contrast occurs at somewhat larger μ than the model predicts. But the agreement seems reasonable, given the difference in wavelength between the IR observations and the model, and also the small sample of faculae we have observed here.

We also consider the explanation for the rather loose spatial correlation found here between infrared facular areas and Ca K plage. Some of this imperfect correspondence may be caused by time differences of up to two hours between the Ca K and 1.63 μm data compared here. The contribution of this time difference needs to be removed in the future by obtaining near-simultaneous and exactly coregistered data in the IR continuum and in strong lines showing the chromospheric faculae.

But at least some of the looseness in this correlation seems to be real. It is likely that the underlying faculae structures giving rise to chromospheric Ca K emission cover a range of sizes (e.g., Zwaan, 1981), so the factors affecting the relative efficiency of chromospheric and photospheric heating might change substantially over this range. For instance, as found by Knölker and Schüssler (1988), larger diameter (50–1000 km) flux tubes than those modeled by Deinzer *et al.* (1984) can actually exhibit a deficit in T_b *within* the structure at $\mu = 1$, while still appearing bright near the limb. The model indicates that the continuum contrast of such "intermediate-size" flux concentrations is considerably larger near $\mu = 1$ than for clusters of the smallest facular flux tubes.

Thus, the size of the facular elements might influence the 1.63 μm contrast more sensitively than it affects their Ca K plage intensity. Further comparison of 1.63 μm images, together with cospatial and near-simultaneous images at different continuum wavelengths, should provide a new way to determine the subresolution structure of such faculae.

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